Plasma interpenetration Study – fully explicit kinetic Particle-in-Cell simulations

Kinetic Physics Workshop

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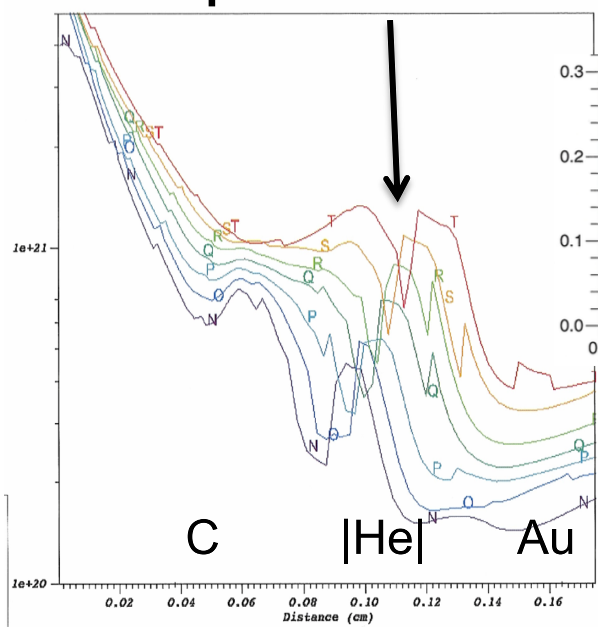
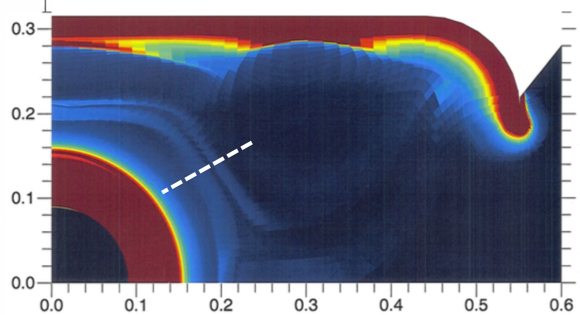
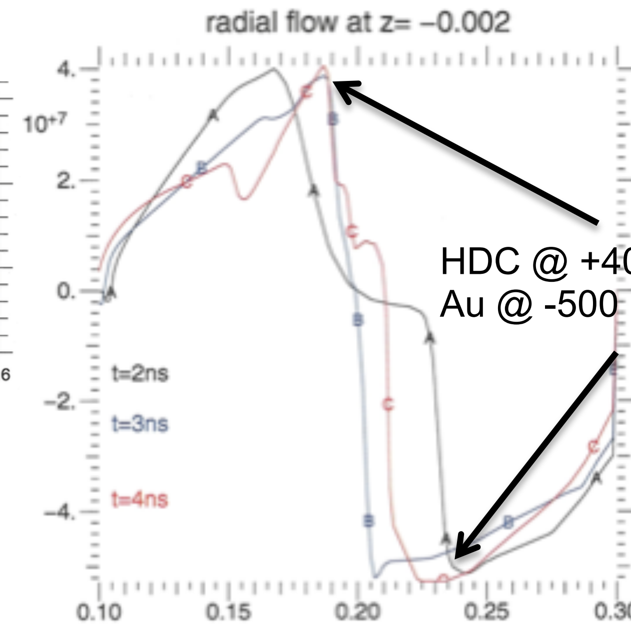
Plasma parameters from 2D HYDRA simulation of Near-Vacuum Hohlraum

800 km/s relative velocities, Ne~1e20-1e21,T~ 1-2 keV, L ~ 1mm

Pile-up at ~ 10-15% crit







Ordering of velocities:

$V_{th,Au} = 3\text{x}10^{6} < V_{th,C} = 10^{7} << U_{rel} = 8\text{x}10^{7} << V_{th,e} = 1.3\text{x}10^{9}$ [cm/s]

For reference, define $kT \sim mU^2/2$

T_{au} = 600 keV ; T_c = 40 keV

Electron thermal energy is converted into ion kinetic energy (quasi-neutral expansion) at impact this is converted into ion thermal energy (stagnation)

We use a traditional Particle-In-Cell code to model this scenario

Conventional PIC Algorithm + Monte-Carlo collisions

Integrate Maxwell's Equations

$$\frac{\partial \mathbf{E}}{\partial t} = c\vec{\nabla}\times\mathbf{B} - 4\pi\mathbf{j} \qquad \frac{\partial \mathbf{B}}{\partial t} = -c\vec{\nabla}\times\mathbf{E}$$

Compute Forces

Accelerate Particles

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{\gamma c}\mathbf{u}\times\mathbf{B}\right)$$

Push Particles

Deposit Charges/Currents

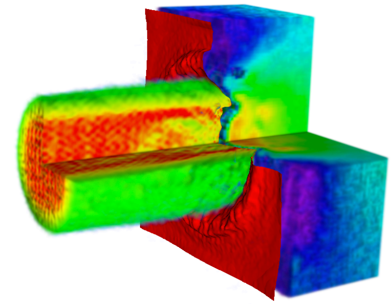
Smooth currents

PIC- MCC

Binary Collisions

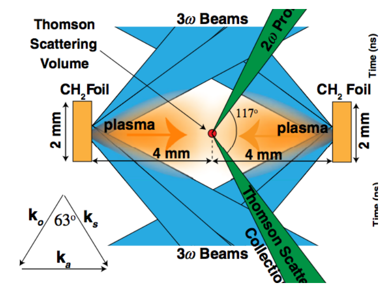
~~Impact Ionization~~

$$\upsilon_{\alpha\beta} = \frac{4\pi^{3/2} q_\alpha^2 q_\beta^2 \ln\Lambda n_\beta}{m_{\alpha\beta}^2 u^3}$$



[20μm diameter flat-top PW pulse]

PIC+coll at solid density (PRL 2012)

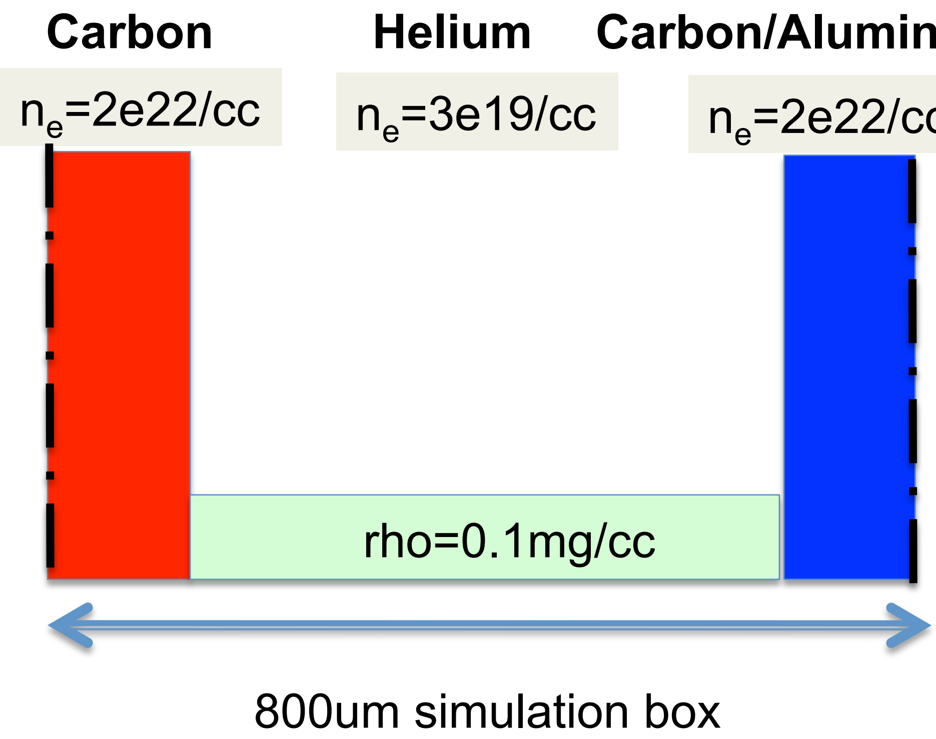


Collisionnal/collisionless plasma heating at low density in counterstreaming plasmas (PRL 2013)

- Binary collision model should reproduce all regimes of interest:
  - Ballistic counter-streaming of ions (stopping power)
  - Diffusion of ions (small angle scattering)
  - Resistive heating
  - Electron heat transport (non-local; two-stream?)

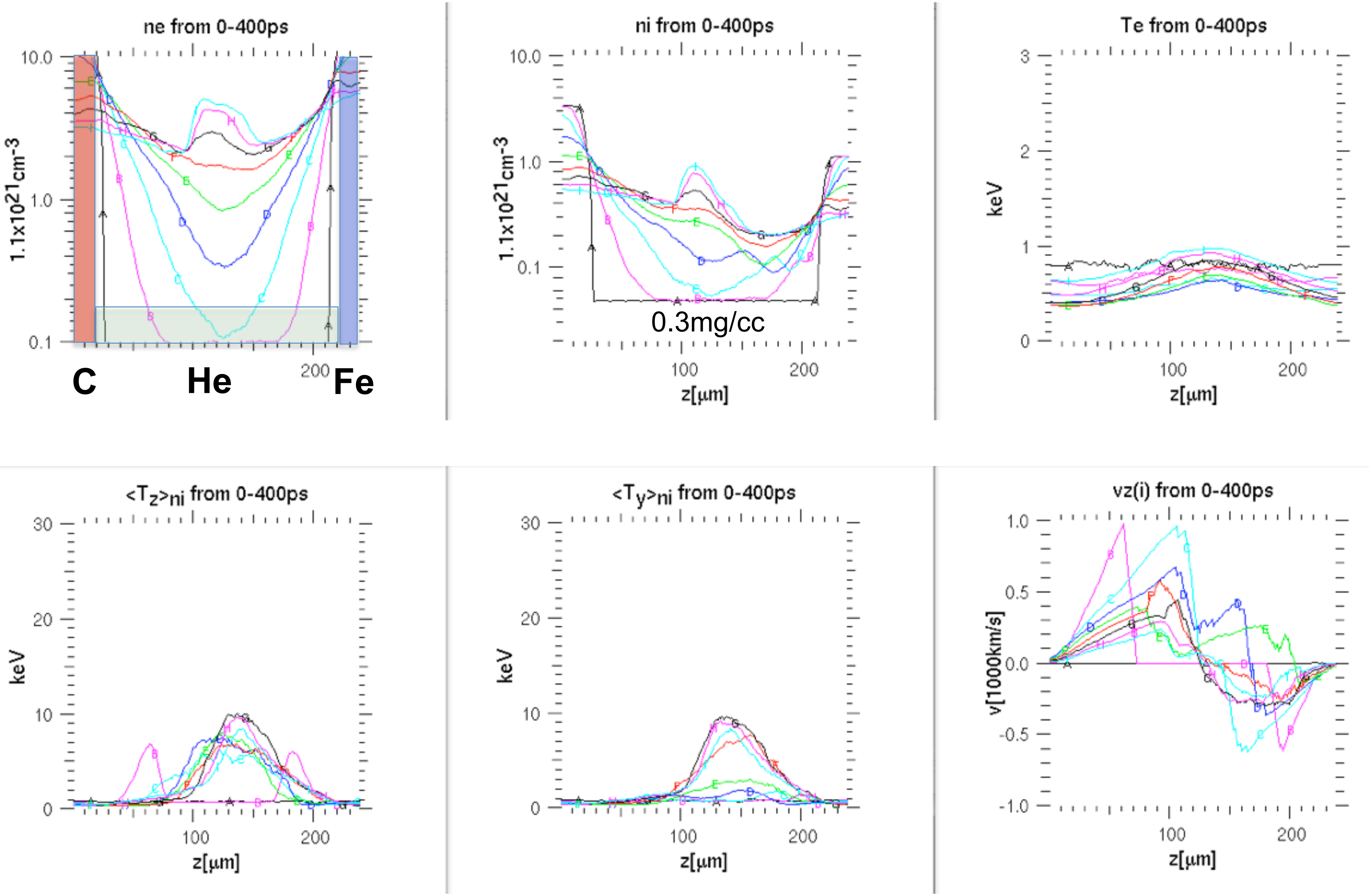
Ruhl, 'Introduction to Computational Methods in Many Body Physics', Ed. M. Bonitz, Rinton (2005). Kemp et al. Phys. Plasmas 11, 5648 (2004)

For kinetic simulations we define an equivalent 1D initial-value problem at reduced scale in HYDRA

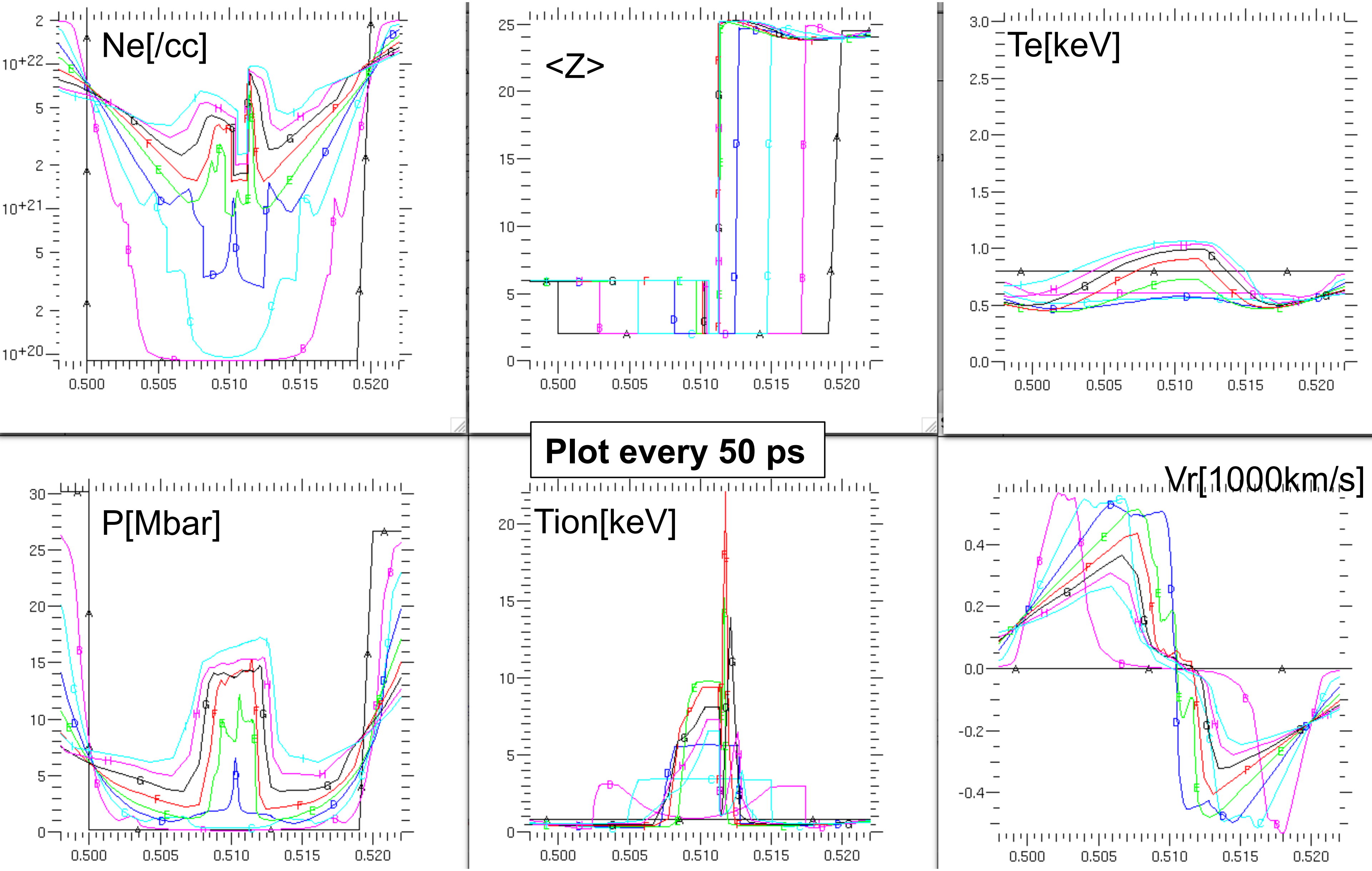


- Te=Ti=800eV everywhere; n_e=2nc
- 40um $C^{+6}/Al^{+11}/Fe^{+28}$ reservoirs
- Initial conditions - no laser, no rad'n
- 800um 1D simulation box
- Run up to ~1ns
- 10cells per micron, 600 C^{+6} part./cell
  7x smoothing / 3rd order shape
- Uniform particle weight for collision op.
- Parallelism limited to 5cells/cpu
- Cost ~100,000 cpu-h per run

PIC simulation of collision between two isothermal expansions tamped by Helium background – ion K.E. is thermalized while Te ~ const



HYDRA view – He gets "squeezed", higher density ridge on Fe side and Tion spike, but mostly in agreement w. PIC



Numerical constraints of our collisional PIC simulations

- Expect a 'smooth self-similar plasma expansion' w/o plasma waves / 1D instabilities.
- Grid resolution 0.1um, constrained by nudt<<1 & current-smoothing for numerical stability
- Uniform particle weight (for collision operator), lower than gas-fill plasma – large particle numbers
- Reflective b.c. for particles, wide enough particle reservoir (40um)

conserve energy to within 10% over 1ns =6Mio time steps

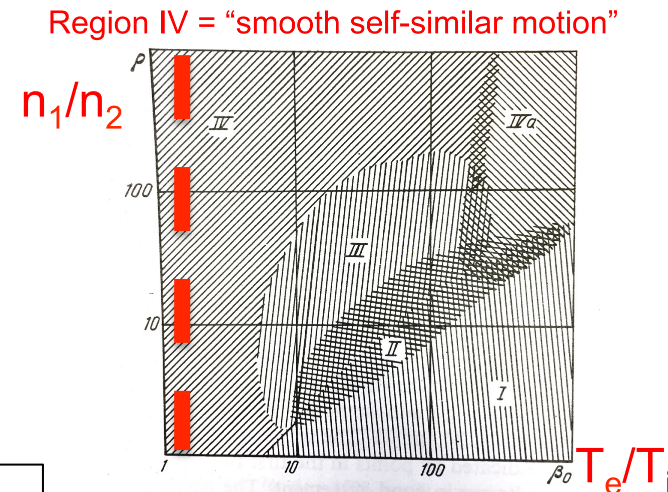
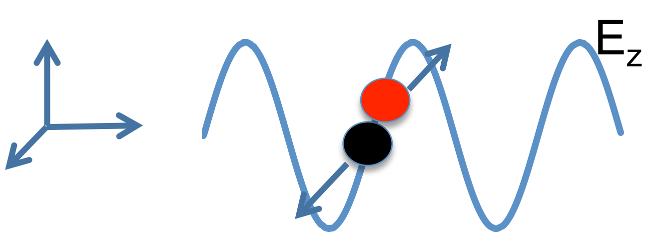


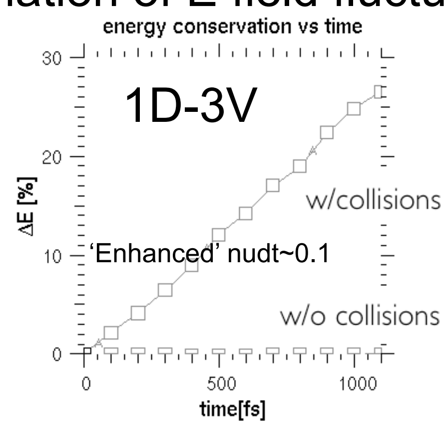
FIGURE 22. Classification of the domains of motion.

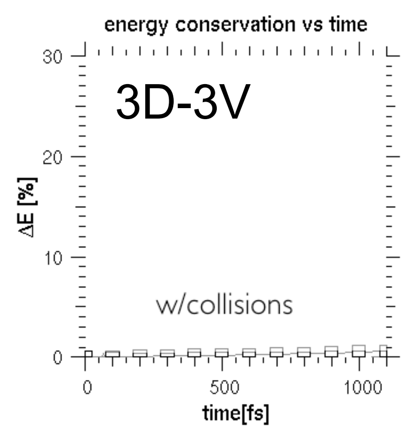
A.V. Gurevich et al, "Non-linear Dynamics and Acceleration of Ions when A Plasma Expands into a Plasma", Sov. Sci.Rev. 13 (1989)

- Self-heating in 1D is caused by combination of E field fluctuations and collisions:

$$\frac{< E^2 >}{2} = \frac{n\,(\gamma - 1)}{8N_D}$$







Coulomb logarithms are based on an interpolation between various limiting cases (*)

with

$$k_D^2 = \sum_\gamma \frac{k_{D\gamma}^2}{1+\sigma_\gamma^2}, \quad k_{D\gamma}^2 = \frac{4\pi n_\gamma Z_\gamma^2 e^2}{T_\gamma},$$

$$\sigma_\gamma^2 = \frac{m_\gamma}{T_\gamma}\left\{ \frac{1}{\frac{m_\alpha}{T_\alpha}+\frac{m_\beta}{T_\beta}} + \frac{\mathcal{U}^2\left(\frac{T_\alpha}{m_\alpha}+\frac{T_\beta}{m_\beta}\right) + \frac{1}{2}\left|\vec{\mathcal{U}} \times (\mathrm{u}_\alpha - \mathrm{u}_\beta)\right|^2}{3\left(\frac{T_\alpha}{m_\alpha}+\frac{T_\beta}{m_\beta}\right) + (\mathrm{u}_\alpha - \mathrm{u}_\beta)^2} \right\}, \qquad \text{(A-3)}$$

$$\vec{\mathcal{U}} = \frac{\frac{m_\alpha}{T_\alpha}(\mathrm{u}_\alpha - \mathrm{u}_\gamma) + \frac{m_\beta}{T_\beta}(\mathrm{u}_\beta - \mathrm{u}_\gamma)}{\frac{m_\alpha}{T_\alpha}+\frac{m_\beta}{T_\beta}}.$$

A.4 Results and discussion

We finally write the Coulomb logarithm for collisions between particles α and β in the form

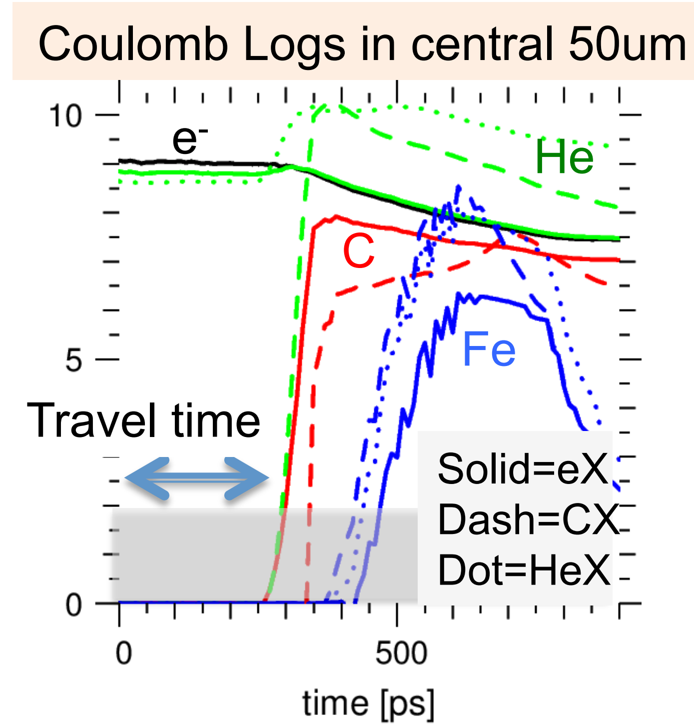
$$\boxed{\ln\Lambda_{\alpha\beta} = \ln\left(\frac{k_{max}}{k_D}\right),}$$

with

$$k_{max} = \min\left(\frac{m_{\alpha\beta}\langle V^2\rangle}{Z_\alpha Z_\beta e^2}, \frac{2m_{\alpha\beta}\sqrt{\langle V^2\rangle}}{\hbar}\right),$$

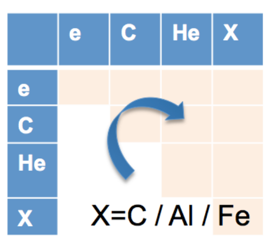
$$m_{\alpha\beta} = \frac{m_\alpha m_\beta}{m_\alpha + m_\beta}, \quad \langle V^2\rangle = 2\left(\frac{T_\alpha}{m_\alpha}+\frac{T_\beta}{m_\beta}\right) + (\mathrm{u}_\alpha - \mathrm{u}_\beta)^2$$

and k_D defined above in (A-3).



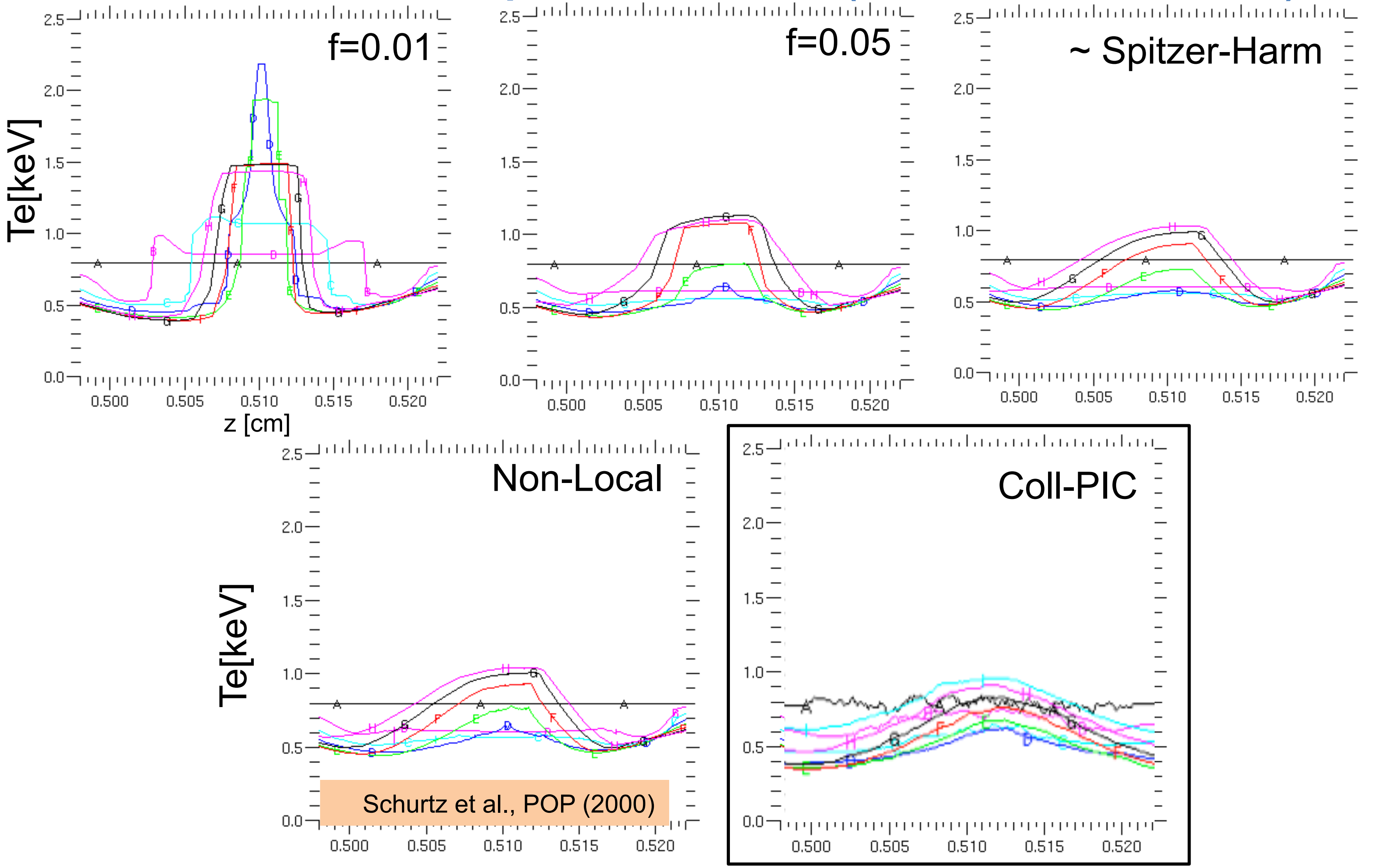
Symmetric 4x4 matrix for e-e / e-i / i-i collisions that covers limiting cases:

- single plasma
- multi-species plasma
- test particle in plasma



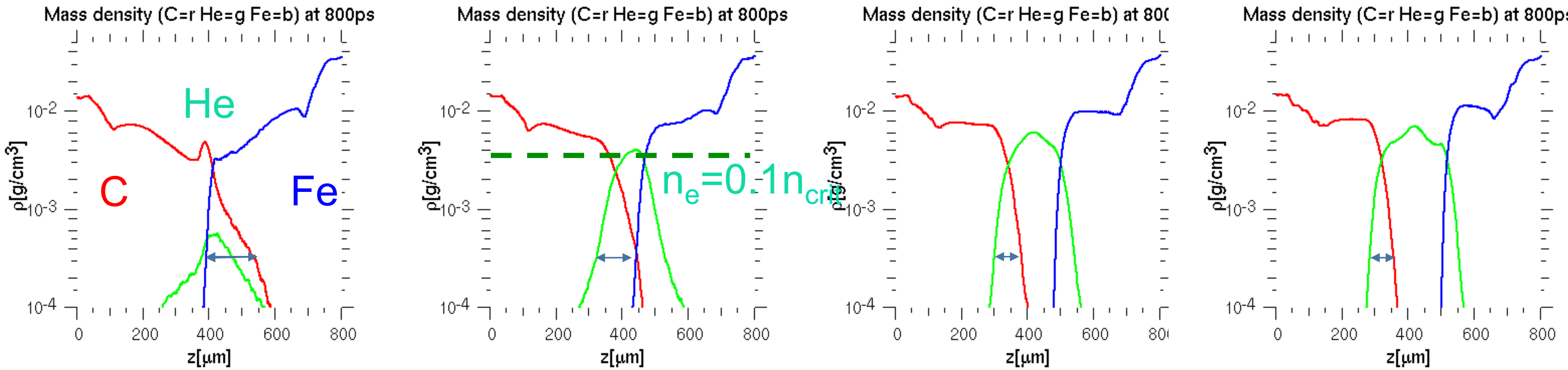
(*) Raviart, Ed. 'Collisions in Plasmas'

Collisional PIC electron heat transport consistent with HYDRA Non-Local-Electron-Heat Transport *a la Schurtz* (or no flux limiter here)



Remaining discrepancy likely due to non-local-ION-heat transport and Joule heating

Scaling with He gas fill density – He does not provide much tamping until n_e>10% ncrit(@3w)



He density= 0.11mg/cc

He density= 0.6mg/cc

He density= 1.1mg/cc

n_e(He,t=0)=0.015 x n_e (Carbon,t=0)

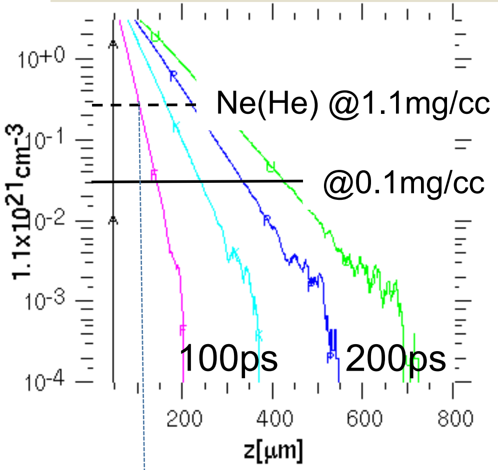
He density= 1.6mg/cc

'Free' isothermal expansion stops when ne(Carbon)~ne(He)

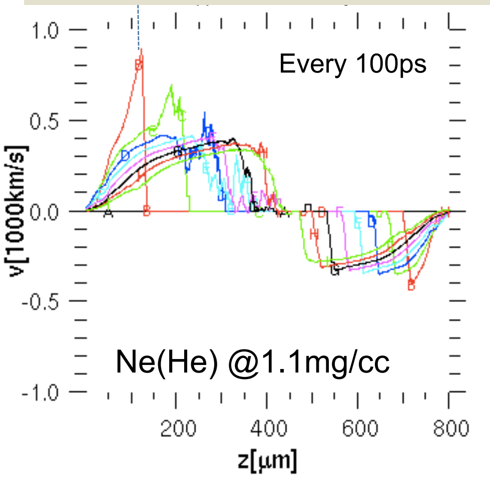
These He mass densities do not translate directly to a hohlraum initial gas fill (early compression; LEH losses; different electron temperatures…)

Scaling with He gas fill density – from fast impact to slow squeeze

n_e for C – vacuum

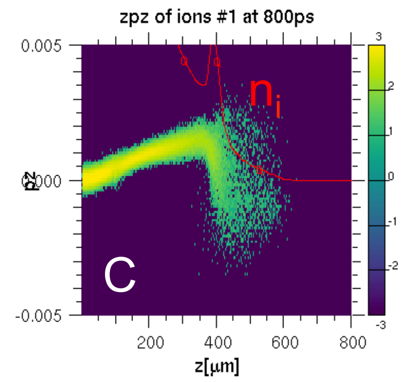


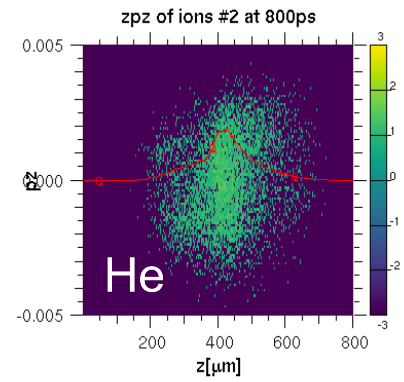
v_z for C-He-Fe

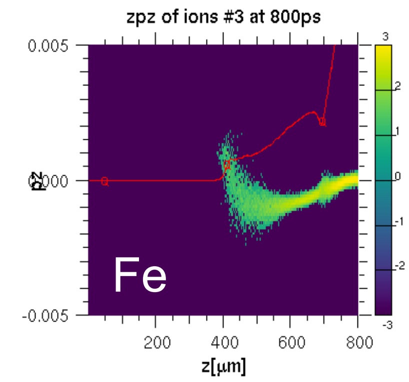


He: 0.1mg/cc

Ion position-velocity phase space

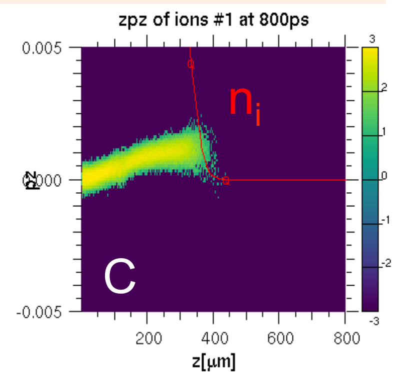


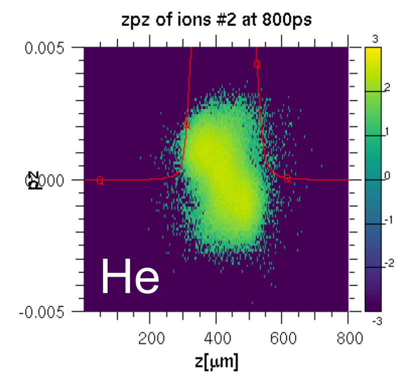


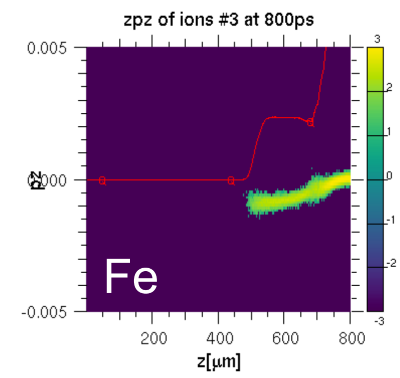


10x higher He density

He: 1.1mg/cc

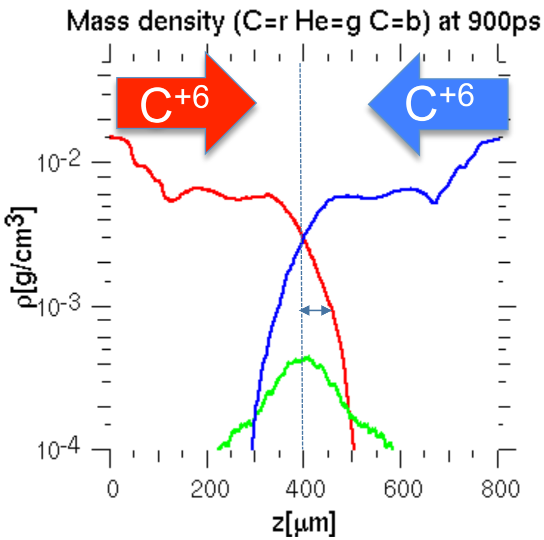


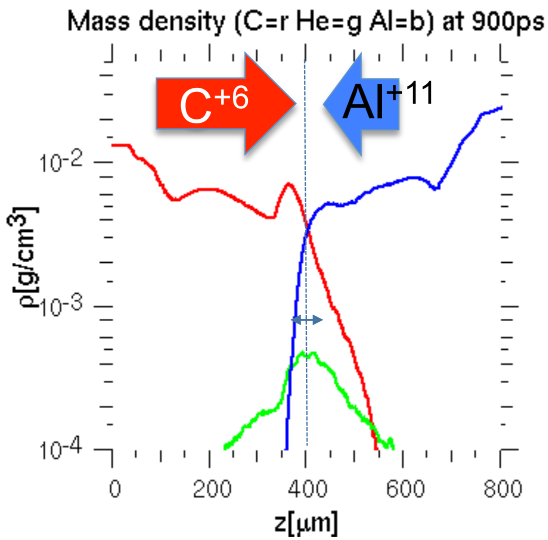


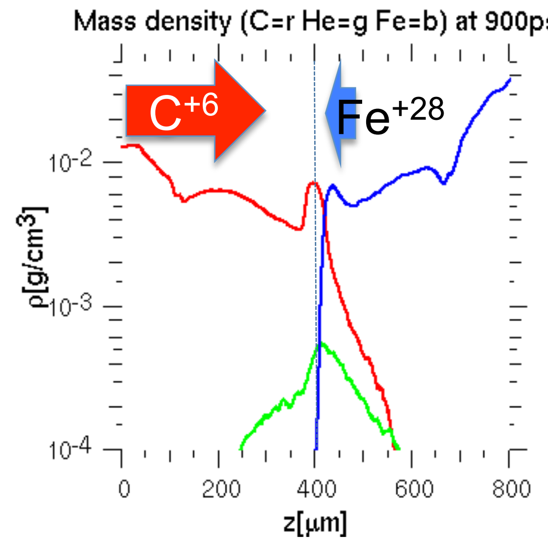


Scaling with plasma Z_{ion} from the right hand side: ion diffusion

C He C	C He Al	C He Fe







Rho(He)=constant=0.11mg/cc

Mix-width of RHS ions	Δz=50um	Δz=25um	Δz<10um

Collision times:

- tau(i-e,slow-down)>>tau(i-i, diffusion)
- $tau_{a\text{-}b,diff} \sim 1/(Z_a^2\, Z_b^2\, n_b)$
- Ion-ion diffusion mix-width ~1/Z

Conclusions

- We model the tamped collision of two expanding plasmas, as found in, e.g., NIF-NVH platform or S.LePape's OMEGA expt., with collisional PIC simulations
- Simulations are numerically converged – using a binary collision operator (TA) with a sophisticated expression for Coulomb Logarithm between all species
- Simulations agree with HYDRA results using non-local electron heat conduction
- Study parameter space spanned by plasma volume, Z, rho(He)
    - Expansion is stopped either by tamping through fill gas or ion-ion diffusion
- Could go to electro-static PIC but limited by collisional time step nudt<<1

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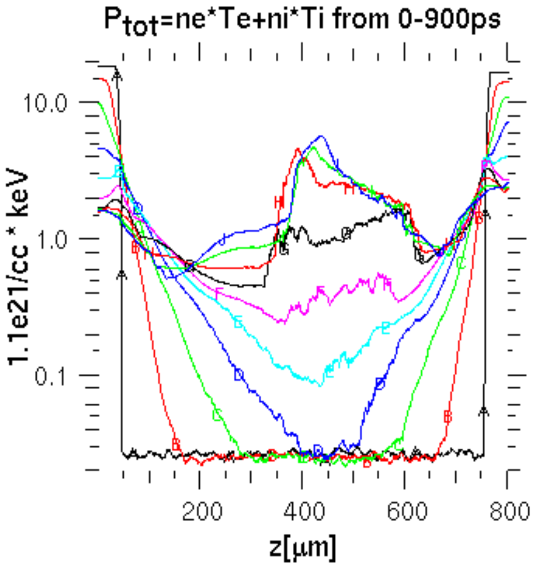
Pressure vs He fill density

0.11mg/cc



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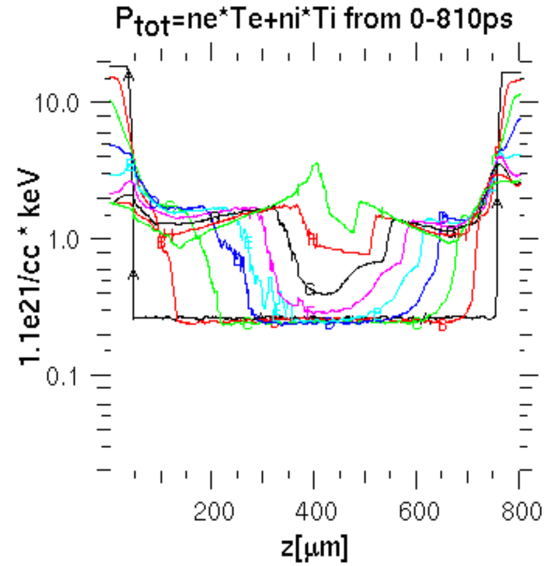
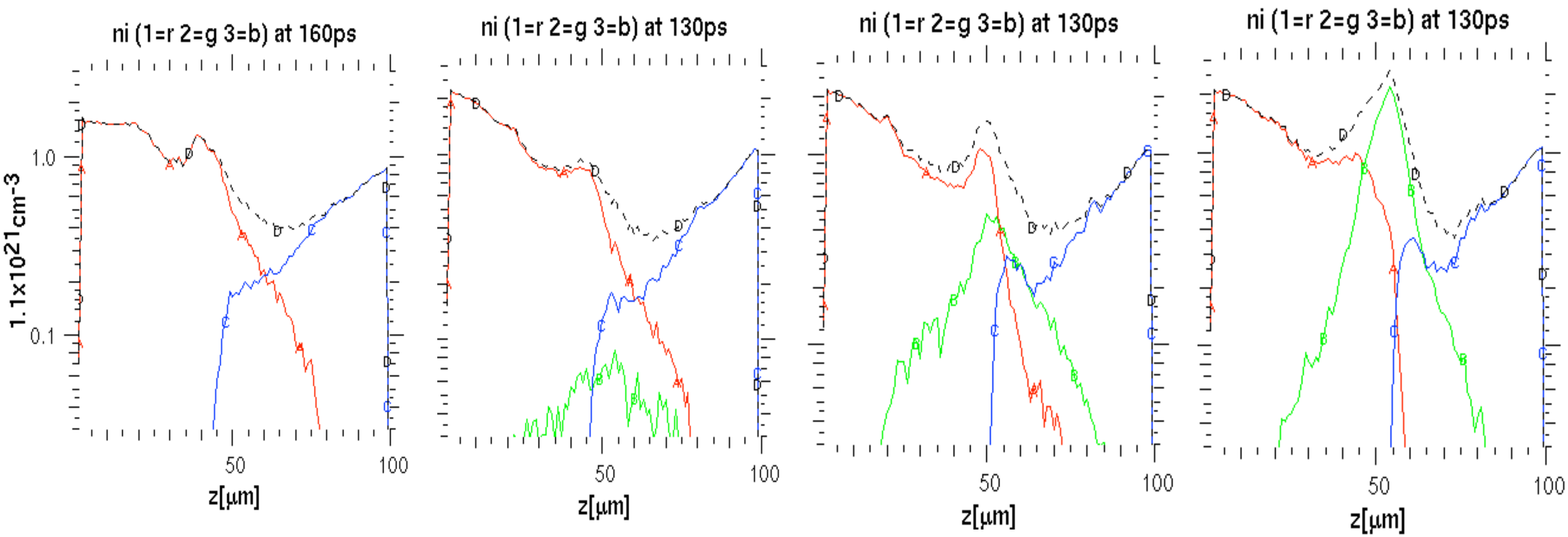
1.1mg/cc



/g/g92/kemp7/INTERPENETRATION/CHEFE800UM1log/

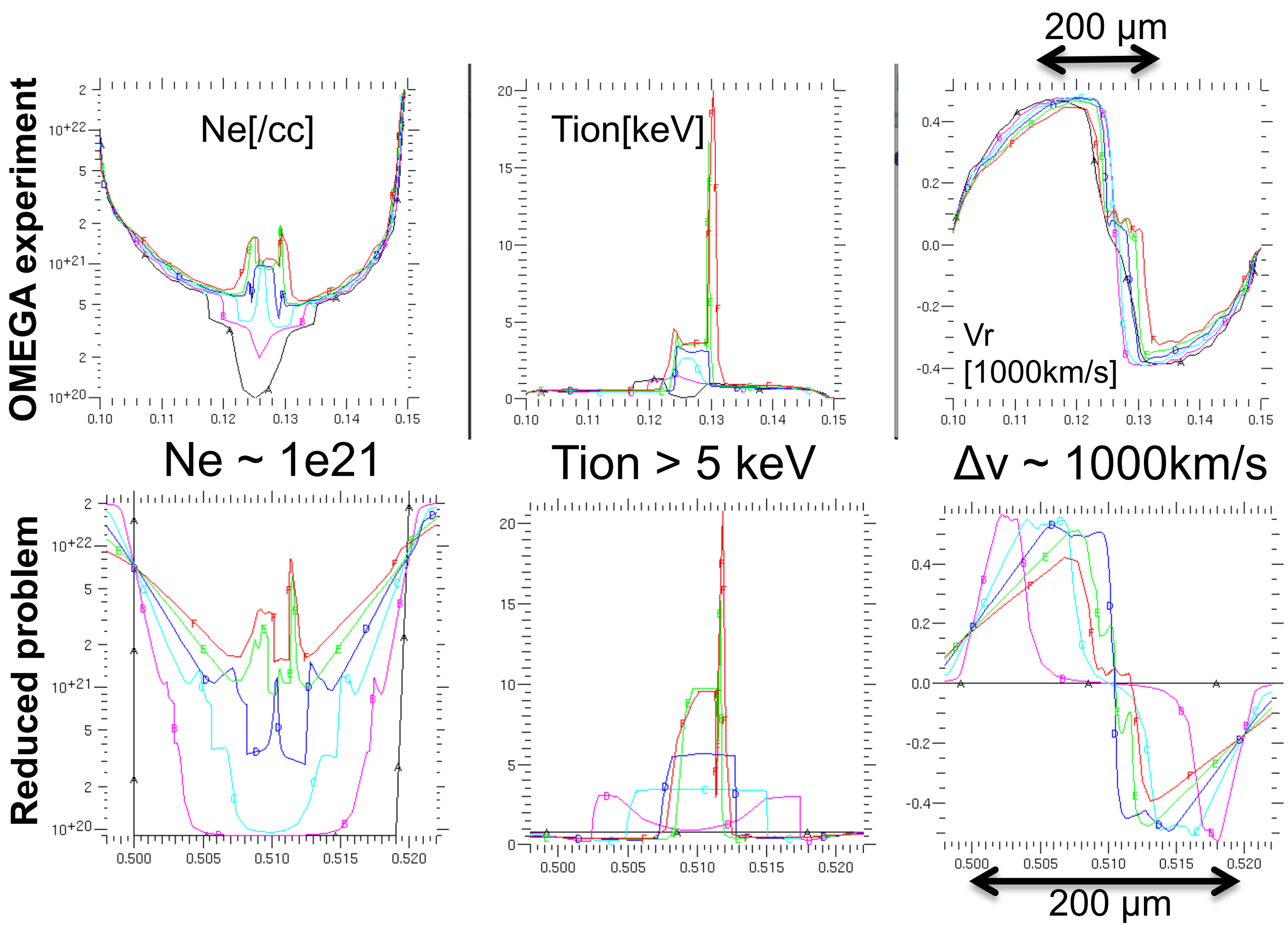
Helium doesn't provide much tamping until Ne > 10% crit



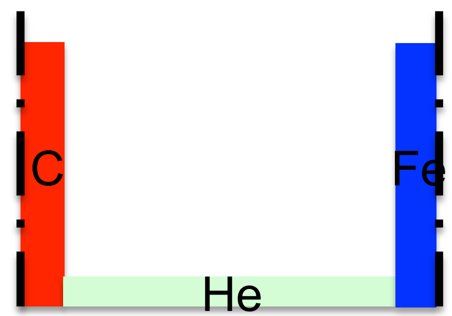
He density : 0 (Vacuum)	He density : 0.3 mg/cc	He density : 1.2 mg/cc	He density : 3 mg/cc

These He mass densities do not translate directly to a hohlraum initial gasfill (early compression; LEH losses; different electron temperatures…)

For kinetic simulations we define an equivalent 1D initial-value problem at reduced scale in HYDRA



Set-up for Particle-In-Cell (PIC) collisionnal simulations
(1 run ~ 24 hours on 512 CPUs)



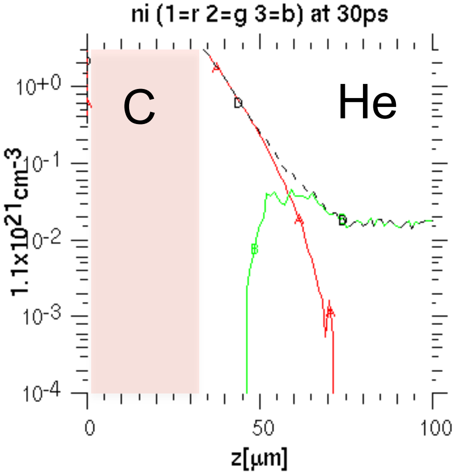
Fe ≅ Au

This initial value problem (isothermal Te=Ti=0.8 keV, no laser, no radiation, lower "solid density" = 2e22) with simple boundary conditions shows similar physics, over 200 µm and 400 ps.

Key features of the early expansion are numerically converged

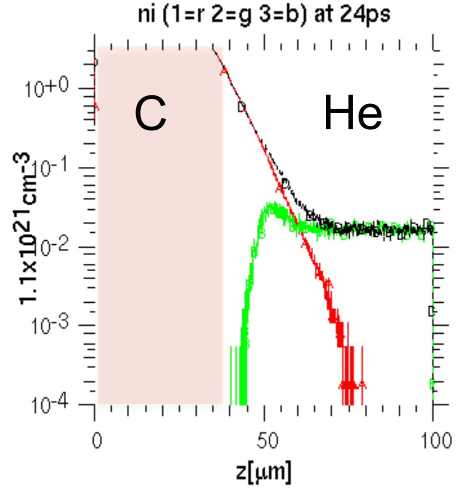
Carbon expansion into He @ 0.1mg/cc:

‘reference case’ after 30ps



- Expansion velocity limited to $1.5\text{x}10^8$cm/s due to He fill gas

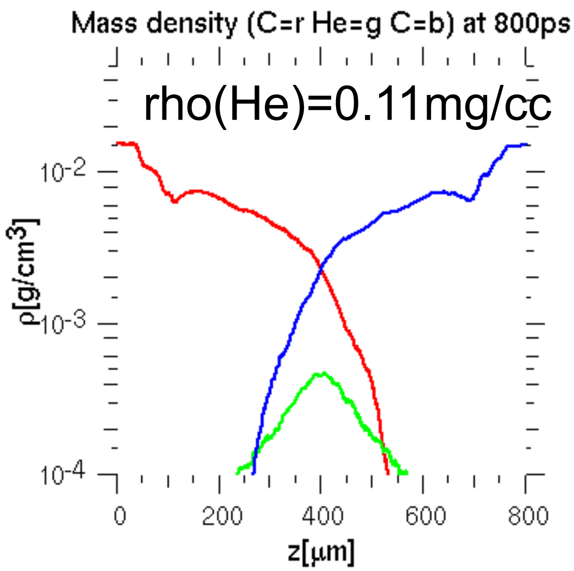
10x resolution ~ Debye length



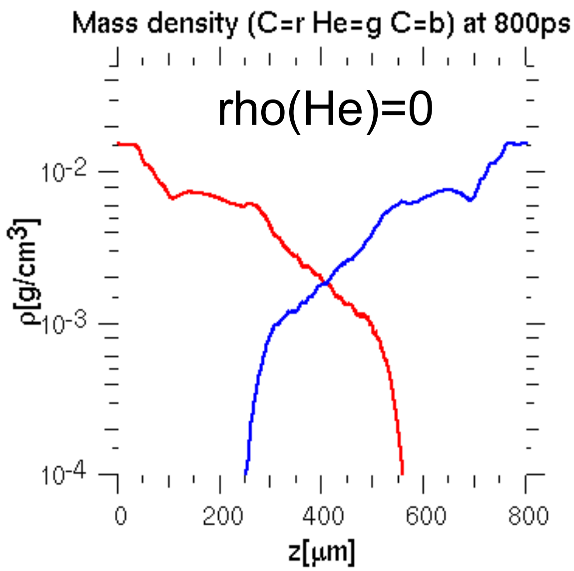
- C-particle weight is lower than He density so max velocity determined by physics not particle weight
- Initial T(He) makes no difference

< 0.1mg/cc He fill gas has little impact on the plasma expansion

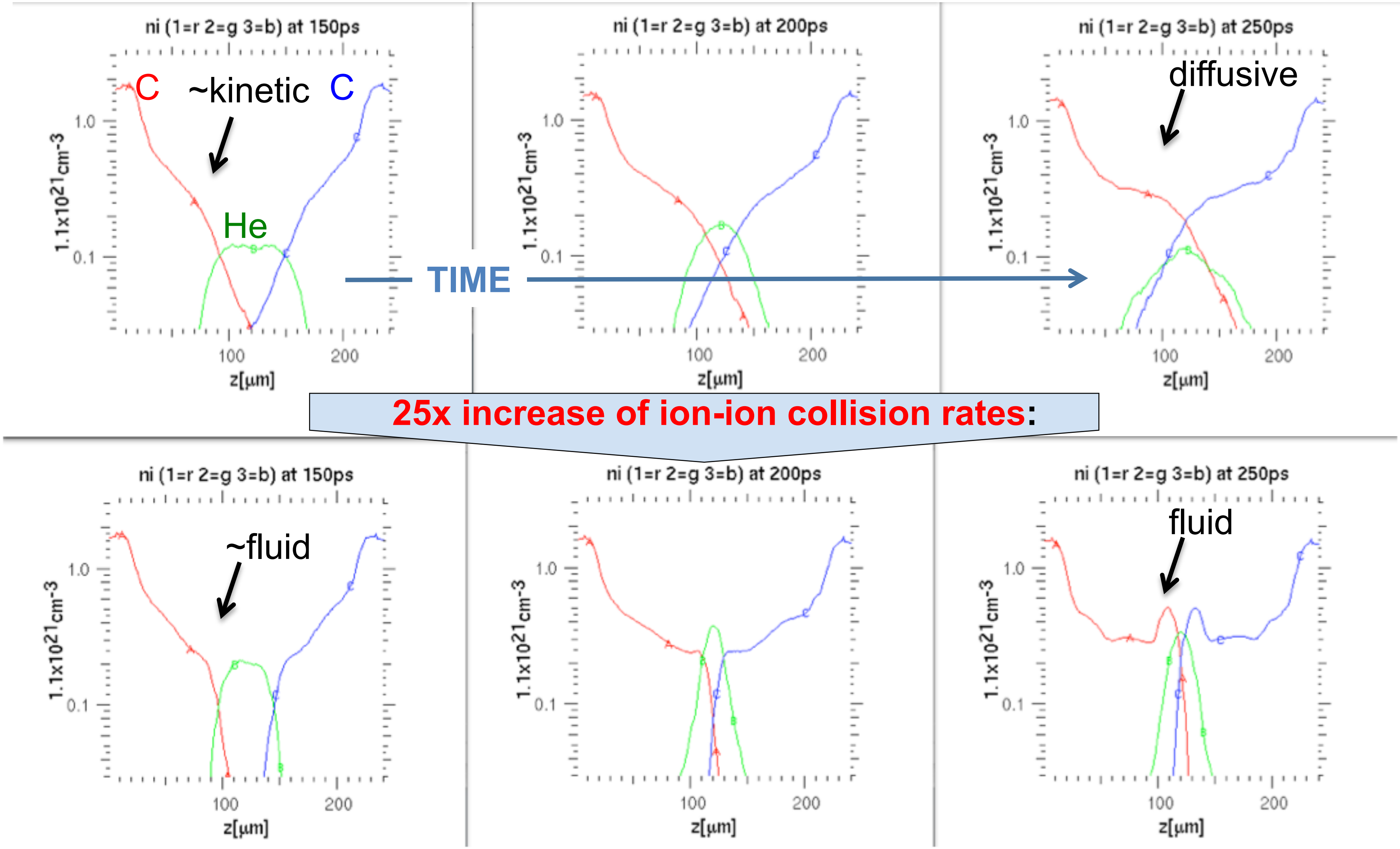
With fill gas



Without fill gas



C-He-C collisional-PIC simulation: ions are mostly interpenetrating early, followed by ion heating/diffusion/stopping when density increases



HYDRA view of this problem : very similar to PIC with 25x collisions